

## **ACEHR REPORT ON NEHRP EFFECTIVENESS - 2021**

### **EXECUTIVE SUMMARY**

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The Advisory Committee on Earthquake Hazards Reduction (ACEHR) provides a biennial assessment of the National Earthquake Hazards Reduction Program as required by the committee charter and Public Law 108-360 as amended. ACEHR is charged with assessing (1) the effectiveness of NEHRP in performing its statutory activities and any needed revisions; (2) the management, coordination, implementation, and activities of NEHRP; and (3) trends and developments in the science and engineering of earthquake hazards reduction.

## INTRODUCTION

The National Earthquake Hazards Reduction Program (NEHRP) Reauthorization Act of 2018 (PL 115-307 or the Act) is a significant milestone for the nation. Since NEHRP was originally enacted in 1977, there has been significant progress by each of the NEHRP agencies (NIST, FEMA, NSF, and USGS) toward advancing the objectives of the Program. As a result, the earthquake community has made considerable strides in understanding earthquakes and reducing earthquake risk through basic and applied research on earthquake processes and earthquake engineering, hazard mapping, improved design and construction practices, stronger building codes and standards, public education, and community-based emergency response programs, among other activities (NRC, 2011; Leith, 2017; references are listed at the end of the report).

The benefits derived from the federal investment in earthquake hazard mitigation far exceed the costs. A recent study (NIBS, 2018) found that federally funded earthquake hazard mitigation grants between 1993 and 2016 saved society \$5.7 billion at a cost of only \$2.2 billion—a benefit-cost ratio of approximately 2.6:1. The savings are due to reductions in loss of service (34%) and reduced damage to property (26%), casualties (19%), and direct and indirect business interruption (21%). This 23-year period was characterized by moderate seismic activity in the U.S.; the benefit that will be realized in future, large earthquakes is likely many times greater. Despite this progress, earthquakes still pose a substantial threat for the nation. All 50 states and several U.S. territories are vulnerable to earthquakes, and nearly half of the U.S. population lives in areas with moderate or major seismic risk. A large earthquake in a major urban center could cause thousands of casualties, widespread population displacement and social disruption, and billions of dollars in economic losses.

Et cetera ...

## ASSESSMENT OF PROGRESS

### *NEHRP Strategic Plan for FY22-FY29*

One of the recommendations from ACEHR's 2019 Report is that the NEHRP Office and agencies should (i) ensure that adequate resources are devoted to developing the updated NEHRP Strategic Plan required by the Act and (ii) report to ACEHR on progress toward completing the Strategic Plan. The NEHRP Office and agencies have addressed both recommendations during the past two years. Furthermore, ACEHR members have been invited to review and comment upon drafts of the Strategic Plan as subject matter experts. This iterative process of sharing Strategic Plan drafts is viewed as a positive one, both from the perspective of engaging the expertise of ACEHR members in the strategic planning process and from a desire to ensure transparency and timeliness in communication. Continuing this same collaborative approach to developing and refining the current and future NEHRP Strategic Plans is strongly encouraged.

As of the May 24, 2021 ACEHR meeting, it was understood that a draft of the NEHRP Strategic Plan was expected to be completed by summer 2021 for review by the NEHRP agencies followed by the Interagency Coordinating Committee (ICC). After ICC's approval, the NEHRP Strategic Plan will be disseminated broadly for public comment, which ACEHR endorses.

**Once the FY22-29 NEHRP Strategic Plan is approved and adopted, the focus will change to ensuring that the Plan is implemented. ACEHR calls upon Congress, the Administration, and the NEHRP agencies to provide the resources required for full implementation of the Plan, including appropriations and budgetary mechanisms that are closely aligned with the Plan at agency and sub-agency levels.**

### *Interagency Coordinating Committee Meetings*

ACEHR views regular meetings of the ICC as an essential means for the agencies to collaborate on critical issues in a direct and coordinated fashion. ICC meetings resumed in 2019, and a virtual meeting was held in August 2020 at which the ICC reached consensus on the outline of the updated NEHRP Strategic Plan. ACEHR understands that the virtual nature of the meeting resulted in good attendance, and we recommend that future meetings be held virtually if the result is more active participation from agency representatives. ACEHR acknowledges the recent progress in holding yearly ICC meetings and expresses the hope that these meetings will continue. As of the date of this Report, a 2021 meeting of the ICC is pending the availability of a draft NEHRP Strategic Plan for review, agency personnel appointments by the Administration, and developments on the infrastructure initiative.

### *ACEHR Meeting Format*

The 2019 ACEHR Report included a recommendation endorsing the initiative from the NEHRP Office to structure future ACEHR meetings in a manner that focuses on implementation of the NEHRP Strategic Plan at a programmatic rather than agency level. Using the NEHRP Strategic Plan to structure ACEHR meetings gives the Program agencies an opportunity to clarify how the Plan's goals continue to enable coordination, collaboration, and integration among the agencies. ACEHR meetings held since the 2019 report have relied on this structured approach, with a focus on progress toward strategic goals rather than a description of individual agency activities.

This change has been viewed positively by members of ACEHR, who thank the agencies for delivering meeting reports that align with this recommendation.

ACEHR also sees value in having more regular and formalized updates from the NEHRP Office and agencies on recommendations made by ACEHR in the committee's biennial reports. **Thus, ACEHR calls upon the NEHRP Office and agencies to add progress updates on previous ACEHR recommendations as a regular agenda item for ACEHR meetings.**

Lastly, ACEHR sees value in using its meetings as a forum for learning about and discussing potential applications to earthquake mitigation, preparedness, response, and recovery from diverse sources. **ACEHR calls upon the NEHRP agencies to cast a wide, multiagency and multihazard net and solicit reports and presentations for ACEHR meetings that may yield lessons for earthquake mitigation, preparedness, response, and recovery.** Suggested examples include the NSF Natural Hazards Engineering Research Infrastructure (NHERI) Network Coordination Office, NIST National Construction Safety Team, and NIST Community Resilience Center of Excellence (see Appendix).

#### *U.S. Government Accountability Office Assessment of NEHRP*

In addition to the development of an updated NEHRP Strategic Plan, the Act also requires the U.S. Government Accountability Office (GAO) to perform a comprehensive assessment of the extent to which the efforts of the past 40 years under the auspices of the Program have been applied to public and private earthquake risk reduction. ACEHR understands that the GAO has completed the first round of interviews with each NEHRP agency during which each agency responded to verbal questions and that follow-up questions and interviews are ongoing at the time of this Report. The GAO has also finalized its report (GAO-21-129) on EEW and the USGS Earthquake Hazards Program. Once the final GAO assessment report is completed, ACEHR proposes that a future ACEHR meeting be devoted to reviewing and discussing the findings with the NEHRP Office and agencies.

#### *Specific Agency Initiatives*

In addition to the overarching items described above, the NEHRP Office and agencies have made progress on the implementation of various initiatives that address earthquake risk-reduction. The list below contains several highlights of these contributions.

- Functional Recovery - NIST and FEMA jointly submitted a Special Publication (FEMA P-2090/NIST SP-1254) titled *Recommended Options for Improving the Built Environment for Post-Earthquake Reoccupancy and Functional Recovery Time* to Congress in January 2021. This Special Publication is discussed in more detail in subsequent sections of this Report.
- Earthquake Risk Reduction and Preparedness - FEMA's Building Resilient Infrastructure and Communities (BRIC) supports states, local communities, tribes and territories as they undertake hazard mitigation projects, reducing the risks they face from disasters and natural hazards. BRIC is a new FEMA pre-disaster hazard mitigation program that replaces the existing Pre-Disaster Mitigation (PDM) program. The BRIC program guiding principles are supporting communities through capability- and capacity-building;

encouraging and enabling innovation; promoting partnerships; enabling large projects; maintaining flexibility; and providing consistency.

- Earthquake Response and Recovery - In November 2019, FEMA published Post-Disaster Building Safety Evaluation Guidance (FEMA P-2055). The report is an outcome of the Disaster Recovery Reform Act of 2018 (DRRA), which directed FEMA to prepare guidance on best practices for post-disaster evaluation of buildings by design professionals to analyze the structural integrity and livability of buildings impacted by natural hazards, including earthquakes.
- Codes and Standards - Several efforts in the past two years have led directly to the continued development of building codes and standards intended to reduce earthquake risk:
  - In September 2020, FEMA published updated *NEHRP Recommended Seismic Provisions for New Buildings and Other Structures* (FEMA P-2082). It presents a set of recommended improvements to the ASCE/SEI 7-16 Standard on *Minimum Design Loads and Associated Criteria for Buildings and Other Structures*, and nine resource papers on new concepts, suggested future development, and technical information in support of the recommended improvements. Under FEMA's leadership, the NEHRP Provisions is developed and evaluated through an expert-based consensus process to ensure validity and quality of the recommended new changes.
  - In October 2020, FEMA published a Fact Sheet on *Seismic Building Code Provisions for New Buildings to Create Safer Communities* that describes the history and role of codes and standards in enhancing earthquake resilience and FEMA's State Assistance Grant Program.
  - In February 2021, FEMA published a 35-year retrospective on *The Role of the NEHRP Recommended Seismic Provisions in the Development of Nationwide Seismic Building Code Regulations* (FEMA P-2156) that summarizes major technical changes incorporated into the Provisions and provides a roadmap for continued development of the Provisions to address recovery-based resilience.
  - FEMA is providing funding for the ongoing Applied Technology Council (ATC) project on *Update of Seismic Evaluation and Retrofit of Existing Buildings Guidance* (ATC-140-1). The purpose of the study is to investigate and address technical issues regarding the evaluation and retrofit of existing buildings and develop material for the expanded FEMA design applications document that will replace the current FEMA 275 Design Examples document.
  - EO 13717, ICSSC and RP10
  - ASCE 7-16 Tsunami Loads and Effects Chapter 6
  - FEMA/ATC Seismic Code Support Committee
- Earthquake-Related Research Activities -
  - ACEHR recognizes and strongly supports the exceptional track record of NSF in providing support for NEHRP-relevant basic research through standing programs

and other convergent research programs, for example, its Natural Hazards Engineering Research Infrastructure (NHERI) program, which made awards for over \$19M in 2020. In particular, ACEHR encourages the continued focus on Broader Impacts as an important element of NSF's Merit Review Criteria, which often capture the potential impacts on earthquake risk mitigation of NSF-funded projects.

- In 2020 NSF and NIST issued a joint NSF-NIST Disaster Resilience Research Grants (DRRG) competition to solicit proposals for fundamental knowledge pertaining to improved science-based policies, practices, and decision tools for natural disaster resilience. In addition, NSF partnered with the Department of Homeland Security to fund a track for Resilience to Natural Disasters this year in its Civic Innovation Challenge competition. This demonstrates responsiveness to previous calls by ACEHR for joint research programs. ACEHR encourages NSF to continue working with its partner agencies on initiatives of this type.
- The NIST Community Resilience Center of Excellence is focused on the development of system-level models and associated databases to support community resilience decision making. The center's multi-disciplinary team includes experts in engineering, economics, data and computing, and social sciences. Research supports development of metrics and tools that will help local governments decide how to best invest resources intended to lessen the impact of hazards on buildings and infrastructure systems and how to recover rapidly and minimize community disruption. A list of current and completed efforts is presented in the Appendix.

## KEY INITIATIVES

### *Functional Recovery and Community Resilience*

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From the 2019 ACEHR Report: Functional recovery of the built environment and critical infrastructure can be viewed as an essential or foundational element of community resilience. The definition of functional recovery must extend beyond individual structures to encompass constellations of interdependent buildings or infrastructure components. What might have been construed as a technical issue—for example, designing one new building that will experience minimal downtime after an earthquake—is complicated by the reality that communities include both new and existing buildings that interact with each other through the people who occupy and use them. As increasing numbers of components of the built environment and critical infrastructure are designed, built, or retrofitted to enable their functional recovery, communities should be able to respond to seismic events more effectively—in less time, with fewer resources, and at lower social, economic, and political cost.

The Act includes a heightened focus on achieving community resilience and a new requirement for NIST and FEMA to jointly convene a Committee of Experts to assess and recommend options for improving the built environment and critical infrastructure to reflect performance goals stated in terms of post-earthquake reoccupancy and functional recovery time. To comply with this mandate, NIST and FEMA developed a plan of action in which FEMA funded a Project Technical Panel, responsible for report development, and NIST funded a Project Review Panel, responsible for report review. FEMA contracted with the Applied Technology Council (ATC), and the NIST contracted with the Science and Technology Policy Institute (STPI) to facilitate this effort. The Committee of Experts consisted of the Project Technical Panel, with 17 outside experts and representation from all interest groups named in the reauthorization, and the Project Review Panel, with 10 outside experts and similar representation. To facilitate national-level stakeholder interaction, NIST hosted five stakeholder workshops that were used to gather additional information and feedback.

The deliverable from this effort, the joint NIST-FEMA Special Publication (FEMA P-2090/NIST SP-1254), *Recommended Options for Improving the Built Environment for Post-Earthquake Reoccupancy and Functional Recovery Time*, was sent to Congress in January 2021. The publication focuses on seven recommended options that address the development of a framework for post-earthquake reoccupancy and functional recovery objectives; designing and retrofitting new and existing buildings to meet recovery-based objectives; designing, upgrading, and maintaining lifeline infrastructure systems to meet recovery-based objectives; developing and implementing pre-disaster recovery planning; providing education and outreach on earthquake risk and recovery-based objectives; and facilitating access to the financial resources needed to achieve recovery-based objectives.

The Committee of Experts offered four actions that Congress might elect to take, or might choose to encourage other federal entities to perform: (1) support technical development,

specifically the development of regulations and policies along with practical and effective methods for design and retrofit of buildings and lifeline infrastructure systems; (2) incentivize action (e.g., through BRIC grants) by encouraging state and local jurisdictions to adopt recovery-based codes and standards, and engage in recovery-based planning, mitigation, financial, and other enabling activities (e.g., to include references to recovery-based objectives in hazard mitigation plans); (3) encourage the Executive Branch to develop recovery-based seismic design and retrofit requirements for federally owned and leased buildings; and (4) lead the development and implementation of a federal education campaign around earthquake risk and recovery-based objectives and support similar educational efforts by state and local jurisdictions.

One of the most striking lessons from the COVID-19 pandemic is the challenge associated with defining “essential” services and activities, particularly when a disaster extends beyond a brief interlude. This has direct implications for the work on functional recovery and community resilience. A related lesson is the community-specific nature of reaching a consensus and community buy-in on what constitutes “essential” services and activities. While the vast majority of communities accepted healthcare workers as “essential” and therefore needful of safe working conditions, the degree to which other workers and industries were viewed similarly appeared to depend on community-specific characteristics, such as the community’s demographic and economic profile. Communities protested across-the-board mandates that failed to consider their specific needs. Again, this is a valuable lesson for those interested in achieving recovery-based objectives for the built environment and lifeline infrastructure systems.

**ACEHR encourages the NEHRP agencies to explore how they might make actionable the four proposed actions and the seven recommended options in the joint NIST-FEMA report, and move the nation forward with respect to recovery-based objectives and community resilience. This exploration should include identification of the funding and research needed to support the recommendations in the joint NIST-FEMA report.**

ACEHR notes that ATC continues to partner with both FEMA and NIST and has adapted several existing work projects to incorporate a focus on functional recovery, including:

- ATC-138 Project (FEMA-funded) – *Support of Performance-Based Seismic Design of Buildings* – Currently developing functional recovery methods and criteria for designing buildings to meet recovery-based objectives within the FEMA P-58 Methodology platform.
- ATC-150 Project (FEMA-funded) – *Improving the Nation’s Lifelines Infrastructure to Achieve Seismic Resilience* – Reviewing the NIST CGR 14-917-33, Earthquake Resilient Lifelines: NEHRP Research, Development and Implementation Roadmap, and initiating selected activities related to lifelines resilience under Program Element I.
- ATC-152 Project (NIST-funded) – *Developing a Framework for Design of Lifeline Infrastructure Systems for Functional Recovery* – Preparing a NIST report that presents a framework to enable decision making for functional recovery of water, wastewater, and electric power lifeline systems after earthquake events.

While these projects address new buildings and lifeline infrastructure, the joint NIST-FEMA report also attaches significance to existing buildings and the social science mechanisms needed to enable a shift to functional recovery and community resilience. These projects represent a healthy start; more work is needed if the nation's citizens are to support and have confidence in the functional recovery of the built environment and lifeline infrastructure systems.

ACEHR considers it essential that the NEHRP agencies collaborate effectively and efficiently within and between the agencies on the topic of functional recovery and community resilience. This may require discovery of what different elements of the agencies are undertaking vis-à-vis these and related topics, including elements outside the usual NEHRP umbrella to include lessons from research on hazards other than earthquakes. Although different hazards may affect the built environment differently, what the public cares most deeply about is the disruption from normal routines caused by disasters. Gathering public comment on the recovery time both needed and preferred for different types of buildings and different types of industries is an activity that the agencies could facilitate that would positively affect the further development of effective codes, regulations, and policies.

While intentional duplication of effort that enhances communication with key stakeholders (e.g., building owners) is valuable, unintentional duplication is not. Establishing and using consistent terminology in agency communications, along with co-sponsoring and co-participating in the variety of webinars and public workshops being offered, are viewed by ACEHR as critical steps toward effective and efficient collaboration.

**ACEHR encourages the NEHRP agencies to sponsor a multiagency and multihazard workshop bringing together individuals, divisions, etc. working on functional recovery and community resilience and related topics.** The purpose would be to exchange information and plan for facilitating intentional duplication and efficiencies.

#### *Earthquake Early Warning and Social Science Research*

Earthquake Early Warning (EEW) systems detect Primary (P-) wave energy from earthquakes, process this data algorithmically, and send alerts. Depending on the location of the epicenter and the speed of the system, alerts can reach people before the subsequent seismic shear (S-) waves, which bring the ground shaking that can cause earthquake damage. ShakeAlert on the U.S. West Coast is an EEW system, consisting of distributed seismometers (part of the Advanced National Seismic System) in California, Oregon, and Washington to detect shaking; data processing centers in California and Washington to detect and analyze earthquakes; and delivery systems to notify end users involving both public (e.g., the Wireless Emergency Alert (WEA) system, public universities, USGS) and private (e.g., Google) partners (Kohler et al., 2020; Given et al 2018; USGS 2021a,b). Since the September 2019 ACEHR report, USGS and partnering agencies have completed rollouts of EEW in northern California, Oregon, and Washington (USGS, 2021a,b). The ShakeAlert system is currently providing service to these three states, home to 16% of the United States population, which comprises the portion of the U.S. population subject to 73% of the nation's seismic risk.

Benefit cost analyses have shown that advanced warning of shaking from ShakeAlert is expected to trigger automated system responses and human protective behaviors the value of which exceed the costs of building and maintaining the system (e.g., Bouta et al., 2020; Strauss and Allen, 2016). These responses include, for example, slowing high-speed trains, halting surgeries, and giving people a few seconds to drop, cover, and hold on. Increased situational awareness is also afforded by EEW and valued by end users (Allen and Melgar, 2019). However, when the P- and S-wave arrivals are only seconds apart—as is typical of shallow crustal earthquakes in California—and the epicenter is in a population center, EEW may reach those end users after, concurrent with, or only a very few seconds before heavy shaking, limiting the potential benefits (Wald, 2020). The Pacific Northwest is at risk from crustal earthquakes, deep intraslab quakes, and subduction zone megaquakes (from the Cascadia plate boundary off the west coast).

ShakeAlert and EEW development to date has focused on building out still incomplete networks of seismometers (Ebel et al 2020; Hellweg et al., 2020), improving data assimilation and algorithms (Cremen and Galasso, 2020; Ruhl et al., 2019a), and developing and testing delivery platforms (e.g., Minson et al. 2020; Rochford et al., 2018). Progress has been made on all these fronts, but challenges remain. Additional research on offshore ocean sensors (Allen and Melgar 2019) and integration of Global Navigation Satellite System (GNSS) data (Melgar et al., 2020; Minson et al., 2015; Ruhl et al., 2017, 2019b) could improve the value of the system, both for advancing scientific understanding of earthquakes as well as for protecting people and infrastructure. Early visions of the amount of information that could be sent in an alert had to be revised given the time and bandwidth limitations associated with the WEA system, which is evolving but still constrained. While education and outreach efforts have increased markedly in the last few years in line with plans (e.g., CREW 2018), additional research is needed on how best to alert people in differing circumstances, including with differing warning times, varying physical response abilities (e.g., elderly or disabled), and in places with more or less vulnerable infrastructure (e.g., unreinforced masonry). Additional research in engineering and the social sciences is needed to develop the system further and better understand how the system can best inform protective actions. Research on post-alert messaging (McBride et al., 2020) and on how diverse users—such as schools, hospitals, and other places where people congregate, and organizations such as dam operators and refineries operating vulnerable infrastructure—do and can best use EEW is needed (Velazquez et al., 2020). To realize the full benefits of EEW, further investments in evidence-supported education and outreach campaigns are also needed, to increase awareness of EEW and to calibrate expectations of its performance.

**ACEHR calls upon the NEHRP agencies to support additional research in both the engineering and the social sciences to develop EEW further and better understand how EEW can best inform protective actions. ACEHR also calls upon the NEHRP agencies to support further investments in education and outreach campaigns to increase awareness and understanding of EEW.**

## RELATED TOPICS AND ISSUES

ACEHR has chosen to highlight four related topics and issues having significant potential to affect earthquake mitigation, preparedness, response, and recovery. They are learning from the COVID-19 pandemic, multihazard approaches, climate change, and data-driven models and new sensing technology.

### *Learning from the COVID-19 Pandemic*

While the United States has not experienced a major earthquake in the recent past, it has experienced other major disasters such as hurricanes, wildfires, storms, tornados, and flooding. Each of these disasters has supplied important lessons for earthquake preparedness and recovery planning. Perhaps the most salient of disasters to strike the United States - and indeed, the world - in the recent past is the global COVID-19 pandemic. This pandemic, unprecedented in modern times, has impacted every aspect of our lives. Some of the starker impacts of the pandemic have been the significant and disproportionate impacts on low income, people of color, frontline workers and small businesses and their ability to effectively prepare and recover from the health and economic consequences of the pandemic.

The lessons learned in COVID-19 response and recovery provide important insights that should be further studied and applied to research and planning for earthquake preparedness and recovery, including the critical need for individual, family, and small business preparedness. We were reminded that healthcare facilities and those who staff them play a pivotal role in both disaster response and recovery. We were also reminded that community recovery after a disaster depends on open and functioning schools. The pandemic highlighted the negative effects of closed schools and daycares; they include learning loss, loss of community and social interactions for children and their families, loss of reliable nutrition for children, challenges for parents who could not return to work without adequate childcare, and employment stresses for school administrators, teachers, and staff. At the same time, many schools quickly pivoted to online learning, suggesting a way forward that could be replicated following a damaging earthquake—if telecommunications systems are functioning. The essential nature of widespread and economically accessible broadband Internet services was made evident by the pandemic.

In addition to schools and daycares, the pandemic revealed the wide range of businesses and organizations considered essential for societal functioning, everything from healthcare to delivery services, along with whether those organizations had to have a bricks-and-mortar location—or not. The fragility of supply chains was crucially highlighted by the short supply of many everyday supplies and the long-lasting impacts on product availability due to closures of manufacturing facilities and meat-processing plants, disruptions to transportation, and unavailability of workers.

Researchers and policymakers should learn from and apply lessons on the impacts and successful interventions from the pandemic to earthquake preparedness, mitigation, and recovery planning and policy. Those interested in functional recovery and community resilience should pay careful attention to the lessons learned about what society considers essential and the conditions under which those elements of society need a bricks-and-mortar location along with supportive lifeline

infrastructure. They should also observe how society adapted to physical distancing constraints by increasing many people's ability to work, shop, and learn from home while also relying on the continuing ability of some members of society to work outside the home, for example, healthcare workers and grocery employees.

### *Multihazard Approaches*

Those who study earthquakes and their effects on the built environment, lifeline infrastructure systems, and socioeconomic systems have contributed significantly to research and policy conversations around earthquake mitigation, preparedness, response, and recovery. Much of what has been learned about earthquakes, their effects, and the means to mitigate and respond to them offer lessons applicable to other hazards. For example, the broad idea underlying performance-based design applies to buildings affected by wind as well as earthquakes. In the same vein, lessons learned from other hazards and resulting disasters may be considered and adapted by those in the earthquake field.

ACEHR recognizes several potential synergies with planning for multiple secondary hazards associated with earthquakes (e.g., landslides, liquefaction, fires) as well as planning for hazards separate from earthquakes (e.g., wildfires, floods, hurricanes, tornados). Secondary hazards, in particular, may complicate or impact earthquake response efforts; understanding their specific nature along with their likely effects on the buildings and lifelines is essential to effective response. Communication challenges, sheltering needs, evacuation planning, supply chain impacts, and more tend to follow the same paths regardless of the nature of the disaster. Importantly, communities are interested in resuming life as normally as possible as quickly as possible regardless of the nature of the disaster, hence the need for clarifying recovery-based objectives as they relate to the built environment and lifeline infrastructure systems.

With respect to existing buildings and lifeline infrastructure systems, it is well understood in the earthquake mitigation community that most older buildings and lifelines require seismic retrofits or replacement to protect occupants and survive earthquakes. At the same time, these same buildings and lifelines may also need retrofits to address floods, wildfire, and/or hurricane hazards and sustainability goals are also driving owners of older buildings and lifelines to think about weatherization and energy upgrades. Holistic and integrated strategies are needed to address the range of retrofits that may be required of older buildings and lifelines while maintaining affordability and preventing displacement. Seismic retrofits should be considered as part of a suite of upgrades competing for limited funding and financing. Rehabilitating or retrofitting historical buildings provides an additional layer of complexity.

New construction and retrofits/upgrades of buildings are guided by current Building Codes and Standards. Those documents may be considered somewhat holistic in that all structural hazards (e.g., seismic, wind, tornado, snow, flood) are considered within one document. However, for an improved holistic approach, each individual hazard-resistant structural design should consider the results and benefits of the other hazard-resistant designs, and benefit from that synergy. An example is a recent consideration and development of a performance-based design approach for wind, so as to be compatible with current earthquake performance-based design

methods. Coordination of blast design with seismic detailing is another example. This approach may achieve even further synergy when considering the more resilient performance objectives (those above life safety). Further benefits may be achieved when the design approach is also in coordination with non-structural issues such as energy conservation, infrastructure, wildfire, response, city planning, and other social issues. Better communication and coordination are needed within the structural hazard groups (i.e., seismic, wind, tornado, snow, etc.), as well as among the non-structural concerns of energy, infrastructure, and social issues in order to achieve recovery-based objectives and community resilience.

**ACEHR calls upon the NEHRP agencies to encourage the identification and implementation of multihazard synergies thereby enhancing earthquake mitigation, preparedness, response, and recovery.**

### *Climate Change*

Climate change is already affecting the nation with respect to earthquakes. Several issues demand further research and action. These include multihazard issues, induced seismicity from geothermal energy and carbon sequestration, effects of groundwater change on seismicity, and the potential impacts of mitigating climate change, including negative unintended consequences.

Many multihazard issues affecting earthquake mitigation, preparedness, response, and recovery may be linked to climate change. Climate change has the potential to modulate earthquake-induced chains of geologic hazards (Fan et al., 2019), and exacerbate their extent, magnitude, and damages. For example, sea level rise, changes in precipitation patterns, ground water levels, and storm surge—resulting from climate change—appear likely to increase co-seismic tsunami and liquefaction hazards (Li et al., 2018; Murakami et al 2005; Yasuhara et al. 2012). Sea level rise could impact tsunami inundation zones and increase the impact of post-event subsidence, putting more people at risk, requiring additional inundation mapping, and modifying safe escape guidance for at-risk communities. Depending on how rapidly and extensively sea level rise happens, millions of people may lose coastal land and be displaced, which increases demand on development in high risk (dry land) areas. This will also require some infrastructure to be moved/elevated/reinforced (e.g., roads, bridges, utilities) and repaired more often due to increased frequency and severity of damage from incidents.

Climate change may also affect immediate and downstream risks from co-seismic landslides, both directly through soil conditions and indirectly through effects on vegetation (Shen et al., 2020), flooding, infrastructure, and adaptive capacity, vulnerability, or resilience. Locations with more intense rain events or prolonged rainy seasons could see an increase in saturated soils leading to a greater liquefaction and landslide risk during an earthquake. There may also be implications for existing liquefaction and landslide maps.

Additionally, impacts of climate change could exacerbate fires and secondary effects of seismic events. We are seeing dangerous increases in fire activity and behavior due to climate change. At the same time, we are seeing massive encroachment into the wildland-urban interface. During the dry season, fires resulting from earthquake damage could significantly impact response and recovery operations. Also, depending on the severity of the earthquake damages, firefighting resources may not be available.

In addition to considering the multihazard issues, we also note the potential for induced seismicity from geothermal energy and carbon sequestration. At present, the United States leads the world in geothermal electricity generation. In 2020, there were [geothermal power plants](#) in seven states, which produced about 17 billion kWh, equal to 0.4% of total U.S. utility-scale electricity generation.<sup>1</sup> Most geothermal power plants in the United States are in western states and Hawaii, where geothermal energy resources are close to the earth's surface. California generates the most electricity from geothermal energy. The Geysers dry steam reservoir in Northern California is the largest known dry steam field in the world and has been producing electricity since 1960.<sup>2</sup>

In 2021, President Biden announced that the US would aim to cut its greenhouse gas emissions 50 percent to 52 percent below 2005 levels by 2030.<sup>3</sup> Expanding geothermal energy may be key to meeting the country's climate goals and geothermal electricity generation has the potential to significantly increase in capacity in the coming decades.<sup>4</sup> Most geothermal power plants inject the geothermal steam and water that they use back into the earth. This process has been demonstrated to cause induced seismicity<sup>5</sup> and therefore is relevant to those focused on earthquake mitigation, preparedness, response, and recovery. Further research is needed to better characterize and develop efforts to successfully forecast induced seismicity in geothermal fields.<sup>6</sup>

The United States' climate goals may in part be reached by capturing and sequestering carbon from point sources underground in depleted oil and gas reservoirs, saline formations, or deep, unmineable coal beds. The research agenda published by [National Academies of Sciences Engineering Medicine \(2019\)](#) calls for roughly \$1 billion to advance the deployment of carbon sequestration in deep sedimentary reservoirs at large scale over 10–20 years. A challenge to the ambitions of carbon sequestration is the potential for induced seismicity that can cause earthquakes in locations that have not previously experienced them. Once again, further research is needed to understand the potential for such earthquakes and mitigate their impacts.

Groundwater changes resulting from climate change may also affect seismicity (Lundgren 2014). Seismicity changes are known to occur due to changes in groundwater extraction or recharge (e.g., central California) (Amos et al., 2014; Saar & Manga 2003; Tiwari et al 2021). Further, sea level rise and seawater intrusion in coastal areas will affect coastal groundwater levels (e.g., May, 2020), and liquefaction susceptibility (e.g., Risken et al 2015). In addition to seismicity changes, changing groundwater levels and their consequences may contribute to reductions in the lifespan of buildings and their partial or full collapse.

Much remains to be learned about how efforts to mitigate climate change will affect earthquake risk relative to the built environment and lifeline infrastructure systems. Changes to power, gas,

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<sup>1</sup> <https://www.eia.gov/energyexplained/geothermal/use-of-geothermal-energy.php>

<sup>2</sup> <https://www.eia.gov/energyexplained/geothermal/where-geothermal-energy-is-found.php>

<sup>3</sup> <https://www.nytimes.com/interactive/2021/04/22/climate/new-climate-pledge.html>

<sup>4</sup> <https://www.energy.gov/articles/doe-releases-new-study-highlighting-untapped-potential-geothermal-energy-united-states>

<sup>5</sup> <https://www.eia.gov/energyexplained/geothermal/geothermal-energy-and-the-environment.php>

<sup>6</sup> <https://www.sciencedirect.com/science/article/abs/pii/S1364032115008722>

and other utility distribution systems seem increasingly likely as governments adopt laws and codes to reduce/phase out reliance on fossil fuels (e.g., Seattle City Council Bill 119993, February 2021). Changes in land use (e.g., retreating from coastal areas) could also affect tsunami risk. Relocation and retreat from flood-prone areas are receiving increased attention as sea levels rise in the US (e.g., Carey, 2020). Finally, battery and energy storage technologies have been proposed and are being adopted to help integrate solar power into the grid (e.g., Hill et al., 2012), and are likely also to make power grids more resilient to seismic risks (Nazemi et al., 2019).

### *Data-driven Models and New Sensing \Technologies*

LiDAR, InSAR, nodal seismic, and Distributed Acoustic Sensing (DAS) are examples of rapidly developing technologies that can gather terabytes of data per day. Each of these sensing technologies present tremendous research opportunities that will require new approaches. Data management and distribution will have to adapt. On the software side, data-intensive computing approaches, such as machine learning, will need to be developed to take full advantage of these opportunities. On the hardware side, GPU, edge, and cloud computing may all play important roles. It will be challenging to adapt to this shifting sensing and computing landscape, but the payoff could be immense for earthquake mitigation, preparedness, response, and recovery. Open-science principles, including open-source code, open data, and open access to publications are trends that could help accelerate progress and broaden and deepen impact in earthquake science and engineering. These principles are particularly important for early career scientists and have become the norm in, for example, research computing. They enable collaborative work, building on best practices, but come with many challenges—such as how to fund, archive, and peer review research publications—that need to be addressed.

## RECOMMENDATIONS

1. *The NEHRP Strategic Plan.* Once the FY22-29 NEHRP Strategic Plan is approved and adopted, ACEHR calls upon the NEHRP Office and agencies to provide the resources required for full implementation of the Plan at the agency and sub-agency levels.
2. *ACEHR Meeting Format.* ACEHR highly values the NEHRP agencies' shift to focusing on implementation of the NEHRP Strategic Plan at a programmatic rather than agency level for their reporting at ACEHR meetings. ACEHR has two additional recommendations related to the structure and focus of its meetings:
  - a. ACEHR calls upon the NEHRP Office and agencies to add progress updates on previous ACEHR recommendations as a regular agenda item for ACEHR meetings.
  - b. ACEHR calls upon the NEHRP agencies to cast a wide, multiagency and multihazard net and solicit reports and presentations for ACEHR meetings that may yield lessons for earthquake mitigation, preparedness, response, and recovery. This recommendation is closely related to Recommendation 5 below.
3. *Functional Recovery and Community Resilience.* Given the importance of functional recovery and community resilience to the nation's safety, ACEHR reiterates its second recommendation from its 2019 Report here, and adds two additional recommendations related to this key initiative:
  - a. "NIST, FEMA, NSF, and USGS should take ongoing leadership roles in engaging with local, state, and federal agencies and professional organizations to foster consensus on issues related to developing and implementing functional recovery requirements" (ACEHR 2019 Report, p. 6).
  - b. ACEHR encourages the NEHRP agencies to explore how they might make actionable the four proposed actions and seven recommended options in the joint NIST-FEMA report, and move the nation forward with respect to recovery-based objectives and community resilience. This exploration should include identification of the funding and research needed to support the recommendations in the joint NIST-FEMA report.
  - c. ACEHR encourages the NEHRP agencies to sponsor a multiagency and multihazard workshop bringing together individuals, divisions, etc. working on functional recovery and community resilience and related topics to address intentional duplication and efficiencies.
4. *Early Earthquake Warning (EEW) Systems.* ACEHR calls upon the NEHRP agencies to support additional research in both the engineering and the social sciences to develop EEW further and better understand how EEW can best inform protective actions. ACEHR also calls upon the NEHRP agencies to support further investments in education and outreach campaigns to increase awareness and understanding of EEW.
5. *Multihazard Approaches.* ACEHR calls upon the NEHRP agencies to encourage the identification and implementation of multihazard synergies, thereby enhancing earthquake mitigation, preparedness, response, and recovery.

## Appendix - Basic Research Needs

*Understanding of earthquake processes and fundamental improvements* [Anne Meltzer, Greg Beroza, Thomas Heausler, Ann Bostrom]

Developers of current building code and standards for seismic resistant design have historically done a good job of incorporating basic research into code and standard design methodologies. As more resilient performance-based objectives are considered (above the traditional life safety level), future research should be performed with due consideration of implementing those higher performance objectives. Such considerations should extend across the spectrum: from advanced technology methods (e.g., advanced analysis techniques, energy dissipating devices, new seismic systems), as well as to the other end of the spectrum which includes simple and affordable methods such as elastic strength approaches applicable to wind governed buildings in low seismic regions.

Developers of current building code and standards for seismic resistant design have also done a good job codifying new cutting-edge research and methodologies into building codes and standards. Recent successes include performance-based design approaches for high rise buildings, base isolation, energy dissipating devices such as dampers, as well as new seismic resisting systems such as buckling restrained braced frames and composite steel and concrete shear walls. The development of these types of cutting-edge advancements should be continued, and results communicated through education guides and seminars. This cutting-edge area may be considered the tip of the pyramid. There is also a need to promote and educate the base of the pyramid. The base of the pyramid may be defined as designs in medium to low seismic design hazard areas, and/or small one and two story, lightweight structures where seismic may not be the governing hazard concern; or where traditional practice may be to incorrectly ignore seismic design as being necessary. For practitioners in these areas, education should be provided regarding the current seismic design methods, as well as development of new simplified methods and education of those new methods.

- Exploit new technologies to learn much more from future earthquakes. This would include ANSS, but also geochronology, LiDAR, InSAR, SfM, ...
- Collect on-scale data on the strength of shaking with sufficient density to understand its spatial variability during large earthquakes.
- Understand how nonlinearity affects faulting, ground motion, and building response.
- Operationalize deep-learning methods for improved earthquake monitoring.
- Improve earthquake forecast models, for both natural and human-induced seismicity, using observations from high-resolution catalogs.
- Update hazard maps for the entire US on a timely basis (e.g. Hawaii and Alaska).
- Fill the information void in the seconds to minutes between earthquake alerts, when they occur, and routine earthquake reporting.

- Move from empirical ground motion prediction to simulation-based ground motion prediction.

*Research coordination: Networking across disciplines [Doug Wiens, Jon Stewart]*

Coordination on EQ disaster reconnaissance with multiple government, professional and research/university organizations, taking advantage of new technologies and protocols for data collection, archiving, and sharing that have been developed for other hazards (hurricanes & floods - which occur more frequently and provide best practices).

The NEHRP agencies, including NSF, NIST, and USGS, have effective mechanisms in place to undertake reconnaissance following extreme events, and record/archive the data from such investigations. The development of this infrastructure is a major accomplishment that places the U.S. in a global leadership position. One aspect that could be improved is pre-event planning and coordination between agencies and researchers outside of the federal agencies, to ensure efficient and comprehensive recording of essential research datasets.

Following the collection of reconnaissance data, the opportunities for utilization of the data are relatively limited. NSF offers a Rapid program to support follow-up research consistent with NSF priorities, which are mainly related to advancing fundamental science. NIST and USGS occupy the relatively pragmatic side of the research ecosystem, but do not have dedicated programs for utilization of post-event reconnaissance data.

This is a missed opportunity. Too often, the current system leads to a focused activity to collect data that is then underutilized. This can be addressed by establishing dedicated research programs to utilize earthquake data to address practical needs in engineering, public policy, and other fields.

## APPENDIX - NIST Center for Risk-Based Community Resilience Planning (CoE)

Ongoing/completed efforts on Functionality & Recovery of Buildings & Lifeline Systems

Shared: 2 July 2021

Contacts: John W. van de Lindt, Maria Koliou, Paolo Gardoni

### *Buildings*

- Probabilistic models to compute time restoration distribution functions for 19 building archetypes (typical US community building stock) subject to tornado loads [analytical study also validated with long term recovery data from past disaster - Joplin]
- Validated probabilistic delay + repair time stepping models for residential building functionality based on most-likely funding source as a function of household income
- Markov-Chain simulation-based building portfolio recovery model to predict the functionality recovery time and recovery trajectory of a community building portfolio following natural scenario hazard events
- Agent-based community-level simulation models accounting for interdependencies of households, lifeline systems, critical facilities, schools and businesses for evaluating recovery times accounting for different hazard scenarios as well as decisions/policies.

### *Lifeline networks - water*

- Physics-based probabilistic model for climate change dependent storm surge
- Probabilistic models to capture the performance of deteriorating infrastructure at the component and network level
- Topology-based and flow-based approaches to quantify the reliability and resilience of critical infrastructure
- Classification of infrastructure interdependencies and mathematical formulation to model the defined classes of infrastructure interdependencies
- Integration of physical infrastructure and social systems in communities' reliability and resilience analysis
- Physics-based probabilistic models for the recovery of interdependent infrastructure at the component and network level
- Formulation and algorithms to optimize the recovery of interdependent infrastructure
- Definition and validation of interdependency models for physical infrastructure
- Algorithm for uncertainty propagation and identification of how uncertainties are modeled within each of the three core disciplines of the CoE
- Definition of resolution for individual infrastructure

*Electrical Power Network (EPN)* : CoE R&D on the seismic performance of lifeline systems and their functional recovery:

- An optimization algorithm to support utility operators in their decentralized restoration decisions, particularly when facing poor post-disaster communication, competing functional recovery objectives, and lack of incentives for cooperation.

- A sequential game-theoretic model of interdependent infrastructure network recovery that accounts for lifeline system operators' urgency in repairing their system, a variety of selfish recovery strategies, and an aim to converge to a global community-wide equilibrium.
- Community level one-way dependency model of buildings with EPN to determine functionality based on building damage and availability of electrical power
- A seismic performance assessment model of coupled cyber-physical power and telecommunication systems with call upsurge congestion and retrial effects on power observability and delivery.
- A seismic reliability estimation algorithm for interdependent lifeline systems with rigorous uncertainty bounds, particularly when accounting for time-dependent cyclic interdependencies.
- A criticality assessment of the Texas Synthetic Grid, to showcase the role of transmission system inertia and load shedding in system-wide functionality after planned and random failures as well as targeted damage.
- A contaminant fate and transport hydraulic and criticality analysis of the water distribution network of Lumberton, North Carolina, which explicitly addresses the chief concern of the community after hurricanes: water quality. (This is work in progress, currently modeling E. Coli contamination scenarios).

#### *Dependency/interdependent recovery*

- Functional recovery models for coupled infrastructure systems: A hazard-agnostic dynamic model simulating coupled infrastructure systems' (power, water, and telecommunication) post-disaster performance with the capability of estimating times to different functional recovery milestones, considering facility-level physical and cyber dependency relationships. Case studies are on hurricanes mostly.
- Risk mitigation strategies evaluation for coupled infrastructure systems: A general decision framework to support resource allocation for infrastructure systems based on the criticality of individual facilities for the collective performance of coupled infrastructure systems. Case studies are on hurricanes mostly.

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